THE RADIAL DIFFUSION COEFFICIENT OF 1.3 - 2.3 MeV PROTONS IN RECURRENT PROTON STREAMS

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Abstract. Direct estimates of the radial diffusion coefficient κ_{rr} for 1.3-2.3 MeV protons in interplanetary space are made by comparing simultaneous observations of the diffusive anisotropy and radial gradient of these particles within recurrent streams. The 1.3-2.3 MeV proton anisotropy has been measured at 1 AU by the Caltech Electron/Isotope Spectrometers on IMP-7 and 8 during recurrent proton events for which measurements of the radial intensity gradient have been reported. The resulting values for κ_{rr} near 1 AU range from (3 to 9) x 10^{20} cm^2/sec, corresponding to scattering mean free paths between 0.03 and 0.1 AU.

Introduction

During periods between the release of large fluxes of energetic particles in impulsive solar flare events, the interplanetary particle fluxes at $\leqslant$ 10 MeV are often dominated by recurrent events, sometimes called "corotating events", because they reoccur at earth with successive solar rotations at ~ 27 day intervals. Until recently, these recurrent fluxes were generally thought to derive from continuous solar emission. However, Pioneer 10 and 11 observations by McDonald et al. (1976) showed that the average intensity of recurrent events near ~ 3 AU was ~ 10 times greater than the average intensity of these events at 1 AU. In a statistical study, Marshall and Stone (1977, 1978) found that the diffusive flow of ~ 1.6 MeV protons at 1 AU during these periods was predominantly towards the Sun, indicating a positive radial gradient, with a source of particles beyond 1 AU and a sink inside. Van Hollebeke et al. (1977) have recently measured the radial intensity variation of 0.9-2.2 MeV protons in individual recurrent events. They find average radial gradients of ~ 350%/AU between 0.3 and 1 AU, ~ 100%/AU between 1 and ~ 3-5 AU, and a negative gradient between ~ 4 and ~ 9 AU.

In this letter we present anisotropy measurements of 1.3-2.3 MeV protons made during recurrent events for which radial intensity variations have been measured by Van Hollebeke et al.(1977). These simultaneous measurements of the diffusive anisotropy and the radial gradient can be used to make a direct estimate of the interplanetary radial diffusion coefficient κ_{rr} which is independent of any particular solution of the propagation equation.

Data Analysis

We have restricted this study to events where the radial intensity variation was measured within the radial range from ~ 0.3 to ~ 4 AU during the period from June, 1973 through April, 1976. As in Marshall and Stone (1977, 1978), it was further required that either IMP-7 or IMP-8 be sunward of Earth, and thus outside of the magnetosphere. If both spacecraft were sunward, we used measurements from the one farthest from the magnetosphere.

The radial gradient G in percent per AU was determined for each period by $G = [100 \ \ell n \ R(r)]/(r-1)$ where R(r) is the intensity ratio at radius r (in AU) compared to 1 AU, as taken from Figure 5 of Van Hollebeke et al. (1977). According to Van Hollebeke (personal communication, 1978), R(r) was determined from averages of $\geq$ 12 hours at time of maximum intensity for each spacecraft. We therefore measured a 12 hour average anisotropy for each event at the time of maximum intensity at 1 AU. In one case, the event of 3/76, the anisotropy measurements could not be made until ~ 3 days after the time of maximum. This event has also been studied by Kunow et al. (1977) who found that the radial gradient of 4-13 MeV protons was approximately constant at ~ 330%/AU throughout the event, in agreement with the 0.9-2.2 MeV proton gradient determined at maximum intensity by Van Hollebeke et al. (1977).

The anisotropy measurements reported here were made with the Caltech Electron/Isotope Spectrometers (EIS) on IMP-7 and 8. Marshall and Stone (1978) have described in detail the measurement of low energy proton anisotropies with the IMP-7 EIS. The IMP-8 EIS is of similar design (see Mewaldt et al. 1976). Relevant parameters for both instruments are summarized in Table 1. For this analysis anisotropies were determined for nuclei which stop in the ~ 50 μm detector D2, including mainly ~ 1.3-2.3 MeV protons, with a small contribution (< 10%) due to He and heavier nuclei. We have used the analyzed event data to determine anisotropies when the D2 count rate PL0 was < 0.3 sec^{-1}, corresponding to a flux of ~1.2 $cm^{-2}sr^{-1}sec^{-1}MeV^{-1}$ for 1.3-2.3 MeV protons, and we have used the sectored PL0 data for periods when PL0 $\geq$ 0.3 sec^{-1}. With this criterion, the measured anisotropies are negligibily affected by the high rate effects discussed by Roelof (1974). The anisotropy direction, which indicates the direction toward which the particles are flowing, is expressed in the solar ecliptic (SE) coordinate system, in which the x-axis points towards the Sun and the z-axis points towards the North Ecliptic Pole.

According to Jokipii and Parker (1970), the observed anisotropy in the anisotropic-diffusion approximation is given by:

$$\vec{\xi}_{OBS} = \vec{\xi}_{CON} + \vec{\xi}_{DIF} = \frac{3}{w} [C(\vec{V}-\vec{V}_E)-(\underline{\underline{\kappa}}\cdot\vec{\nabla}U)/U] \qquad (1)$$

where U is the particle density (4πj/w),$\vec{V}$ is the solar wind velocity, $\vec{V}_E$ is the orbital velocity of Earth about the Sun, $\underline{\underline{\kappa}}$ is the diffusion tensor,

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Table 1. EIS Low Energy Proton Measurements

IMP Space-Craft	Data Type	AΩ (cm^2-sr)	Energy Range (MeV)	Rigidity Range (MV)
7	D2 Events	0.20	1.3-2.3	49-66
	PLO Rate	0.20	1.2-2.4	48-67
8	D2 Events	0.23	1.4-2.3	51-66
	PLO Rate	0.23	1.4-2.5	51-69

w is the particle velocity, $C = -\partial(\ell n\ F)/3\partial(\ell n\ p)$ is the Compton-Getting factor, $F = j/p^2$ is the phase space density, p is the particle momentum, and j is the differential intensity.

The convective term $\vec{\xi}_{CON}$ is proportional to the solar wind velocity $\vec{V}$ and is related to the energy spectrum of the particles through the Compton-Getting factor C. In this study we have fit the spectrum of observed particles with an exponential in particle rigidity P of the form $dJ/dP \propto \exp(-P/P_o)$ where P_o is the e-folding rigidity in MV, since this functional form provides the best representation of recurrent event spectra observed over somewhat greater energy intervals (McDonald et al. 1976; Mewaldt et al. 1978). For exponential rigidity spectra $\vec{\xi}_{CON}$ is given by:

$$\vec{\xi}_{CON} = [3 + P/P_o - \beta^2]\frac{(\vec{V} - \vec{V}_E)}{w} \qquad (2)$$

As was discussed by Marshall and Stone (1978), for the limited energy interval used here (2) gives a result that is negligibly different from the more conventional definition of $\vec{\xi}_{CON}$ in terms of a kinetic energy power law spectrum.

The mean value of $\vec{\xi}_{CON}$ for each period was determined by averaging (2) over the rigidity interval of observation (Table 1) using the value of P_o determined from a least squares fit to the observed particle spectrum. Solar wind data were obtained from the MIT plasma experiments on IMP-7 and 8 (J.D. Sullivan and H.S. Bridge, personal communication, 1977) and from King (1977). $\vec{V}_E$ was assumed constant with a value of 30 km/sec in the $-Y_{SE}$ direction. The diffusive anisotropy $\vec{\xi}_{DIF}$ is then obtained by subtracting $\vec{\xi}_{CON}$ from $\vec{\xi}_{OBS}$.

If both the radial component of $\vec{\xi}_{DIF}$ ($\equiv \xi_{DIF,x}$) and the radial gradient G are measured simultaneously, then according to (1), the radial diffusion coefficient can be calculated from

$$\kappa_{rr} = w\xi_{DIF,x}/3G \qquad (3)$$

with the corresponding scattering mean free path $\lambda_r \equiv 3\kappa_{rr}/w = \xi_{DIF,x}/G$. Note that the determination of κ_{rr} from (3) depends only upon the anisotropic-diffusion approximation and not upon a particular solution to the propagation equation.

Additional information on particle propagation can be determined, however, by comparison of the observations with a suitable propagation model. Marshall and Stone (1977, 1978) have discussed a simple model designed to describe their observations of persistent sunward streaming during recurrent events. Starting from the steady-state Fokker-Planck equation, the model assumes azimuthal symmetry, a radial diffusion coefficient κ_{rr} independent of radius and energy, and a source of particles at some r > 1 AU. In this model adiabatic energy loss provides a sink for particles inside 1 AU.

The model makes two predictions which can be tested by the present observations. First, since there is an approximate balance between the convective anisotropy outward and the diffusive anisotropy inward, with a net flow inward to provide particles to the sink, the radial component of $\vec{\xi}_{DIF}$ should be roughly proportional to the solar wind velocity V, since both $\vec{\xi}_{CON}$ and the sink (adiabatic energy loss) are proportional to V. Secondly, the model predicts that ξ_{DIF} should be roughly independent of κ_{rr} and the radial gradient G individually, even though it is proportional to their product.

Observations

Figure 1a shows $\vec{\xi}_{OBS}$ for the 20 periods meeting the above selection requirements. For each period the measured P_o and the solar wind velocity V have been used to determine $\vec{\xi}_{DIF}$, which is shown in Figure 1b. Note that the observed anisotropy is away from the Sun, and roughly normal to the nominal magnetic field direction, while the diffusive anisotropy is in all cases towards the Sun, and approximately along the nominal field. The mean

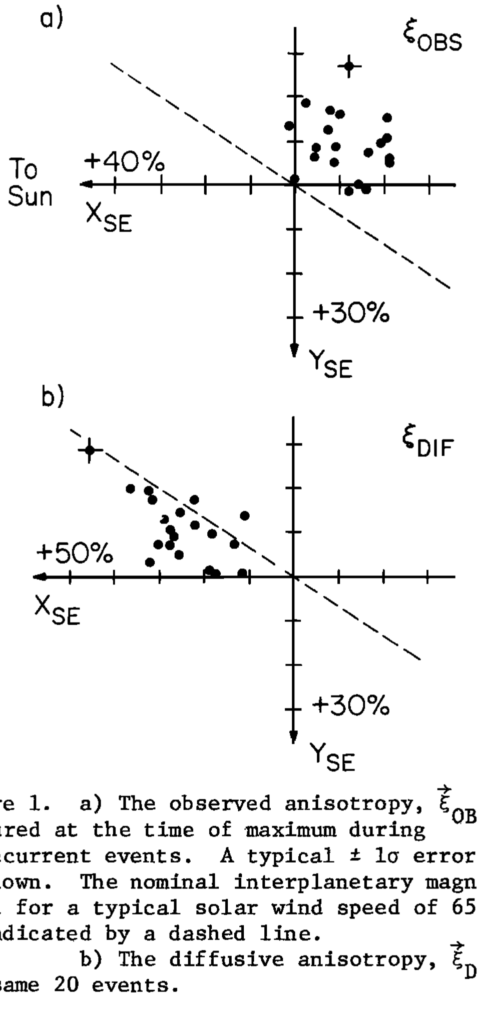

Figure 1. a) The observed anisotropy, $\vec{\xi}_{OBS}$, measured at the time of maximum during 20 recurrent events. A typical ± 1σ error bar is shown. The nominal interplanetary magnetic field for a typical solar wind speed of 650 km/sec is indicated by a dashed line.

b) The diffusive anisotropy, $\vec{\xi}_{DIF}$, for the same 20 events.

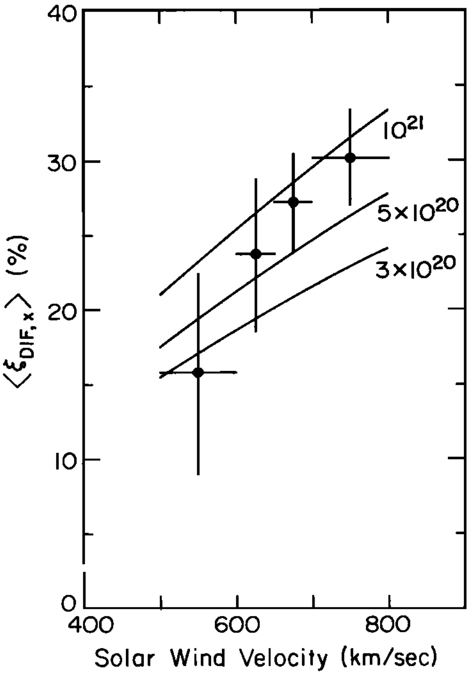

Figure 2. The average x-component of $\vec{\xi}_{DIF}$ as a function of the solar wind speed. The predicted curves were calculated from the model discussed in the text for the indicated values of κ_{rr}.

x and y components of $\vec{\xi}_{OBS}$ and $\vec{\xi}_{DIF}$ are

$$\langle \vec{\xi}_{OBS} \rangle = (-8.4\% \pm 1.6\%, -12.1\% \pm 1.6\%)$$

$$\langle \vec{\xi}_{DIF} \rangle = (27.4\% \pm 1.9\%, -13.0\% \pm 1.8\%)$$

The mean radial component of $\vec{\xi}_{DIF}$ found here is somewhat greater than the value of 14% found by Marshall and Stone (1977). However, the time periods included in the present sample are highly selected and have a mean solar wind speed of ~ 650 km/sec, compared to a mean of ~ 440 km/sec in their study.

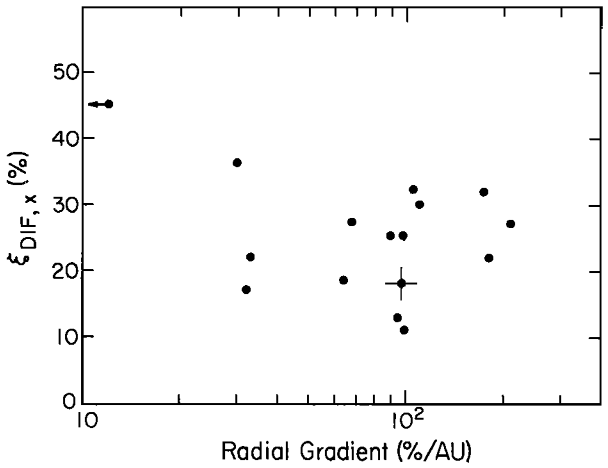

Figure 3. Correlation plot of $\xi_{DIF,x}$ and the large scale gradient for 16 events measured between 1 and 3-4 AU (i.e., with radial separations of 2-3 AU). Typical ± 1σ uncertainties are shown.

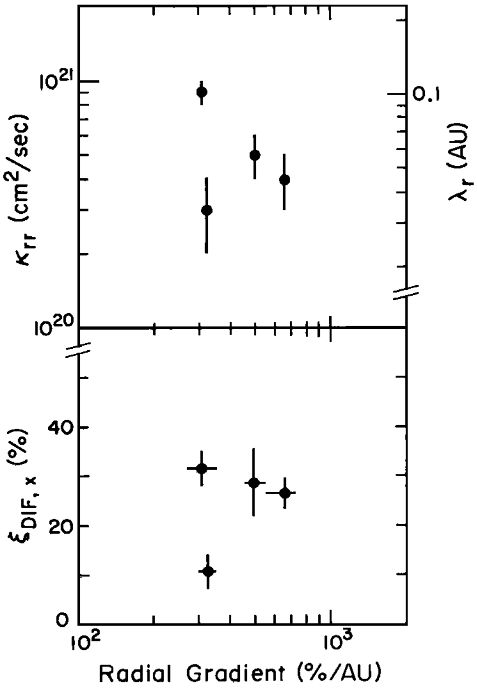

Figure 4. Bottom panel: Plot of $\xi_{DIF,x}$ vs. the local radial gradient for 4 events measured between 0.3 and 1.3 AU. Top panel: The radial diffusion coefficient, κ_{rr}, and corresponding scattering mean free path, λ_r, determined for these events.

In order to investigate the predicted dependence of $\xi_{DIF,x}$ on V, the 20 periods have been grouped according to V. As shown in Figure 2, the observed dependence of the mean anisotropies on V is consistent with the predictions of the model. (Since the predictions depend on the particle spectrum as characterized by P_o, the observed dependence of P_o on solar wind velocity has been included in the model calculation.) From $\langle \xi_{DIF,x} \rangle$ we obtain a first order estimate of $\kappa_{rr} \sim 7 \times 10^{20}$cm^2/sec. Marshall and Stone (1977) employed similar arguments to obtain an estimate of $\kappa_{rr} \sim 4 \times 10^{20}$cm^2/sec for a more heterogeneous data set with lower solar wind velocities.

In order to investigate the relationship of $\xi_{DIF,x}$ and the gradient, it is necessary to separately analyze those gradient measurements near 1 AU (local) and out to ~ 3-4 AU (large scale), since the local and large scale gradients are different in magnitude. Because 16 of the measurements are at ~ 3-4 AU, these large scale gradients were used to examine the correlation of $\xi_{DIF,x}$ and the gradient as shown in Figure 3. Although the lack of correlation between the two agrees with the model, it might also suggest that the large scale gradient is not indicative of the local gradient.

It is likely that measurements of the large scale gradient at least underestimate the local gradient, since 3-4 AU is the radial range where the gradient appears to flatten (Van Hollebeke et al. 1977) and may also be in the region where acceleration is taking place (McDonald et al. 1976; Barnes and Simpson, 1976; Pesses et al. 1978). For this reason, only local gradient and anisotropy measurements have been used to derive κ_{rr}. The bottom panel of Figure 4 shows these local measurements for 4 events, including 3 events observed by Helios and one by Pioneer. For these events we have used (3) to determine the values of κ_{rr} shown in the top panel of Figure 4. The values of κ_{rr} range from (3 to 9) x $10^{20}cm^2sec^{-1}$ with a mean of 5 x $10^{20}cm^2sec^{-1}$, corresponding to λ_r values from 0.03 to 0.10 AU with a mean of 0.06 AU.

Discussion

There are several other approaches that have been used by others to estimate λ_r from energetic particle observations. In a study of shock-associated events observed by Barnes and Simpson (1976) and Pesses et al. (1978) between 2.6 and 6 AU, Palmer and Gosling (1978) deduced a range of λ_r from 0.021 to 0.64 AU, with a mean of 0.23 AU. Although not directly comparable, the present results are well within this range.

Another method for estimating λ_r is to fit the intensity-time profiles of energetic solar particle events with time-dependent solutions of the Fokker-Planck equation. Zwickl and Webber (1978) have recently compiled and reanalyzed available energetic solar particle intensity-time profiles from 1967-1974 over the rigidity range from ~ 1 to 3000 MV. They find λ_r to be nearly rigidity independent below ~ 500 MV, with a lower limit range from ~ 0.03 to 0.09 AU. Our values from 0.03 to 0.1 AU determined from recurrent events are therefore in agreement with the lower limits determined from energetic solar particle studies. It should be emphasized, however, that the present estimates of λ_r represent a qualitatively different determination from that obtained from studies of solar flare events. The present study depends on the accurate characterization of quasi-steady state properties in the interplanetary medium near 1 AU, while the analysis of solar flare intensity-time profiles requires additional assumptions concerning the integrated effects of injection at the Sun and subsequent propagation from the solar surface out to at least several AU. Secondly, the estimates of λ_r in our study are appropriate to propagation conditions in high speed solar wind streams within which recurrent events are observed at 1 AU.

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